TITLE: G & alpha: Centrifuge Occupant Tolerance to Simultaneous High G and High Angular Acceleration

G & α: Centrifuge Occupant Tolerance to Simultaneous High G and High Angular Acceleration

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Summary

The ability of a centrifuge operated as a Dynamic Flight Simulator to meet the response recommendations of the Federal Aviation Administration (FAA) for motion simulators is discussed. The effect on an occupant of angular acceleration artifacts produced by such an enhanced centrifuge is explored. The concern investigated herein is whether these high angular acceleration artifacts are dangerous, disorienting, or distressing. Human response tests have been conducted on the centrifuge at Wright-Patterson AFB to evaluate sensitivity to the artifacts produced by a centrifuge when operated in this rapid response mode. Results indicate the effect to be no more than a mild disturbance over the expected range of G loading and artifact magnitudes found in the next generation of centrifuges. The unique capability of a Dynamic Flight Simulator is that the pilot can be exposed to high fidelity, sustained, elevated-G levels while receiving training in flight procedures and air combat tactics. Such a capability would be expected to provide improved flying performance during the vestibular and tactile misinterpretations common during sustained acceleration.

Introduction

Ground-based motion simulation of aircraft is currently accomplished with "six-post" or "hexapod" devices. These devices are able to provide motion cues with little addition to the response time a pilot senses. These devices are particularly suited to provide motion cues for aircraft operations (such as landing tasks) where pilot response is critically dependent on the fidelity of the visual and motion cues. Hexapod devices (Figure 1) are not able to provide sustained acceleration. This means that flight fidelity is diminished in many maneuvers such as a basic coordinated turn or critical tactical maneuvers of fighter/attack aircraft. This missing fidelity impacts training pilots to cope with vestibular and tactile illusions that routinely occur in flight, especially at low, but not momentary, inertial forces. Centrifuge-based flight simulation offers the potential to provide sustained G flight simulation. The most fundamental challenge is to provide rapid response with a massive device: 1) whose controlled inertia includes a planetary arm as well as the cockpit capsule (referred to in this paper as the cab); and 2) whose changes in acceleration level result in acceleration artifacts, namely angular accelerations associated with cab rotation, that may degrade the rider's perception of flight. These issues are closely coupled, because rapid response times result in high angular acceleration artifacts. The concern investigated herein is whether these high angular acceleration artifacts are dangerous, disorienting, or distressing.

Definition of Dynamic Flight Simulation

Dynamic Flight Simulation (DFS) is defined in this paper to be operation of a centrifuge as a flight motion simulator with the centrifuge driven by pilot commands in response to a perceived flight condition [1]. It is similar to a hexapod motion simulator in that a pilot provides closed-loop response to out-the-window visual cues, instrument readings and perceived motion cues that have been coordinated to represent aircraft flight. Fidelity of the simulator's response time and accelerations to that of the actual aircraft is critical, as is accurate relative timing of this sensory information to the pilot. The implications for ideal operation are that the math model of aircraft response must compute instantaneously and the centrifuge should respond instantaneously to the math model output [2].

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Tracking delay is the sum of the transport lag and the delay in centrifuge response. Reducing delay is the result of design improvements, such as increased speed of the computational hardware and software as well as increased motor size and reduction of centrifuge mass in motion. Federal Aviation Administration Circular 120-40B specifies how much motion and visual tracking delay can be tolerated in simulators used to train commercial pilots [3]. The simulators for which these specifications were written are hexapod devices that impart only onset acceleration cues that are “washed out” within a fraction of a second [4]. Hence, it does not address the issue of how much lag is suitable for a pilot experiencing periods of sustained acceleration levels above 1 G. It is likely that the pilot will be less sensitive to lag at elevated G levels, but this is a conjecture on the part of some of the authors that needs to be evaluated with human response tests on a rapid response centrifuge.

An improved controller design that is expected to make modern centrifuges capable of satisfying the most strict FAA category recommendations is discussed in another paper by the authors [5]. The correlate of implementing such a control system would be the introduction of very fast repositionings of the cab and thus very high angular accelerations and decelerations imposed on the pilot within. Large angular cab excursions are required because the tangential component of centrifuge acceleration becomes more influential in determining direction of the resultant centrifuge acceleration vector. It is possible that such rapid angular movement, even when coordinated with the desired linear accelerations, may be dangerous without proper restraints, disorienting to the point of disability, distressing to one’s stomach, or otherwise intolerable. This paper describes a brief investigation into the human sensitivity to such rapid angular accelerations at several linear G levels in all three axes (x, y, and z).

Methods

The objective of the tests described herein was to develop a subjective assessment of human perceptual sensitivity to artifacts of angular and linear acceleration at various G loadings. The magnitudes of the angular artifacts investigated were selected to cover the range of angular rates produced in the mathematical model used for the simulator’s control system design (1). The tests were conducted with no task distractions in order to obtain the unmasked sensitivity.

Overall Equipment Set-Up- The Dynamic Environment Simulator (DES, Figure 2), a man-rated centrifuge at Wright-Patterson AFB, was set up in two different configurations: seat facing forward in a tangential direction for roll exposures and seat facing inboard radial for pitch exposures. The visual field consisted of a projected text on a white screen in a dark cab and operation of the flight stick. The seat had a 30° seat back angle. The DES arm speed and cab position were under open-loop computer control with G force experienced in two axes simultaneously. Gz onset rate was the maximum obtainable with arm torque (approximately 0.75 Gz/sec).

Subjects- The test subjects were volunteer members of the DES Sustained Acceleration Research Panel, and had passed all required medical screening and completed indoctrination training. They gave informed consent and were trained in the verbal responses required for measurement.

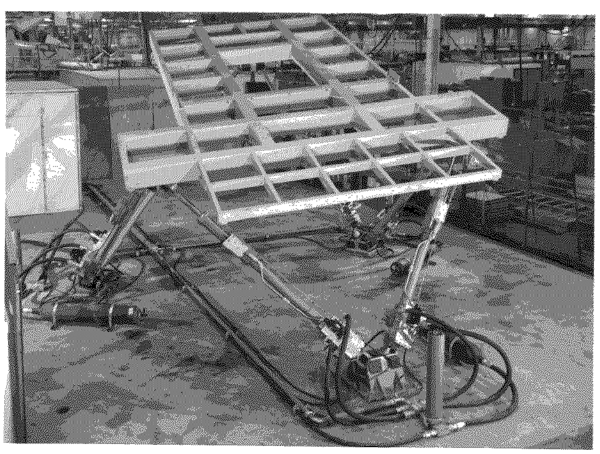

Figure 1. A hexapod motion base.

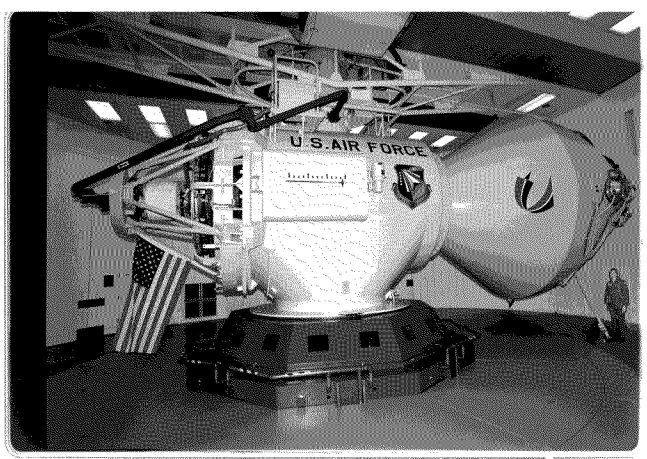

Figure 2. Dynamic Environment Simulator

Experimental Procedures- Subjects were exposed to a series of 0.75 Gz/s onset ramps to plateaus at 1.4, 2, 4, 6, and 8 Gz as well as a control condition at 1 Gz. The plateau lasted 12 seconds. During the plateau, they also experienced a roll pulse. During plateaus at 4, 6, and 8 Gz the pulse was sustained for 4 seconds while during plateaus at 1, 1.4, and 2 Gz it was momentary. The magnitude of the pulse was varied according to Table 1 and the onset of the pulse was at a set alpha rate of 1, 2, 4, 7, or 10 radians per second squared, also found in Table 1 (note each separate test profile is designated by a letter). The entire table of conditions was repeated in the pitch axis. There were 7 subjects, each experiencing 3 repetitions of the tests described above. After returning to baseline, subjects verbally responded with a numerical indication of the intensity of the perceived artifact. The Artifact Response Rating (ARR) scale was:

0 = did not feel at all
2 = noticed it
4 = felt but not disruptive
6 = felt and caused some distress
8 = felt and caused significant discomfort
10 = totally unacceptable

Profile Name	Gz	Gx	Peak Alpha (rad/s^2)	Cab Displacement (degrees)	Transition Time (sec)
A	1	0.5	10	26.57	0.68
B	1	0.5	7	26.57	0.81
C	1	0.5	4	26.57	1.07
V	1	0.5	2	26.57	1.51
D	1.4	0.5	10	19.47	0.58
E	1.4	0.5	7	19.47	0.69
F	1.4	0.5	4	19.47	0.92
W	1.4	0.5	2	19.47	1.30
G	2	0.5	10	14.04	0.49
H	2	0.5	7	14.04	0.59
I	2	0.5	4	14.04	0.78
J	2	1	10	26.57	0.68
k	2	1	7	26.57	0.81
l	2	1	4	26.57	1.07
x	2	0.5	2	14.04	1.10
m	4	0.5	4	7.13	0.55
n	4	1	4	14.04	0.78
o	4	1.5	4	20.56	0.94
y	4	0.5	1	7.13	1.11
z	4	1.5	1	20.56	1.88
p	6	0.5	4	4.76	0.45
q	6	1	4	9.46	0.64
r	6	1.5	4	14.04	0.78
s	8	0.5	4	3.58	0.39
t	8	1	4	7.13	0.55
u	8	1.5	4	10.62	0.68

Table 1. Conditions for each of 26 profiles.

Results

Pitch Results- The 26 profiles were analyzed in 4 comparisons in which one of the factors (Gz or Gx) was fixed at one level so that an analysis could be performed for the other 2 factors. The dependent variable was the mean rating (ARR) across the 3 repetitions for each subject and profile. Repeated measures analyses of variance were performed using subject interactions as error terms. These four analyses are represented in Figures 3-6 and show the relationships among the three conditions of Gz, Gx, and alpha. Figure 3 shows that the ARR was not affected by alpha, as long as Gx was low. Figure 4 shows that ARR was unaffected by alpha magnitude but increased with increased Gx when Gz was low. In other words, it was the Gx that bothered subjects, not the rate of the pitching motions. Figure 5 shows that ARR is a function of both linear

components, but in opposite directions, showing more sensitivity when in high Gx and less sensitivity when in high Gz. Figure 6 shows that even at a moderate Gz level, ARR is not sensitive to alpha, but still shows response to the Gx component. These results suggest that high angular artifacts need not be a serious concern in DFS design. All rates from 1 to 10 radians/ sec^2 were rated nearly the same subjectively, regardless of the G level attained. Subjects showed considerably more sensitivity to increasing Gx bias than to increasing angular acceleration spikes, and high Gz somewhat masks both effects. A summary of the results is contained in Table 2. Though not statistically significant, there was a trend for faster alpha to be preferred at lower Gz levels.

Roll Results - Methods of experimental design and analysis were identical to the Gx portion of the experiment. Table 3 shows the results for the lateral artifacts. The trend for faster alpha to be preferred at lower Gz levels was not observed in the roll artifacts.

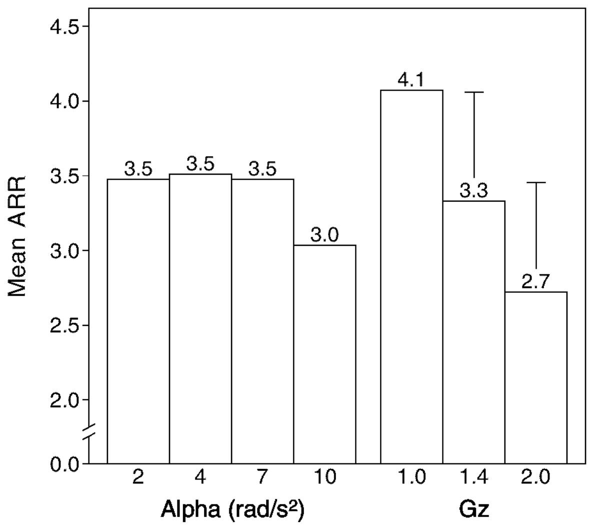

Figure 3. Main effect means. Gx=0.5. Whiskers are minimum significant difference from the Bonferroni paired comparison procedure.

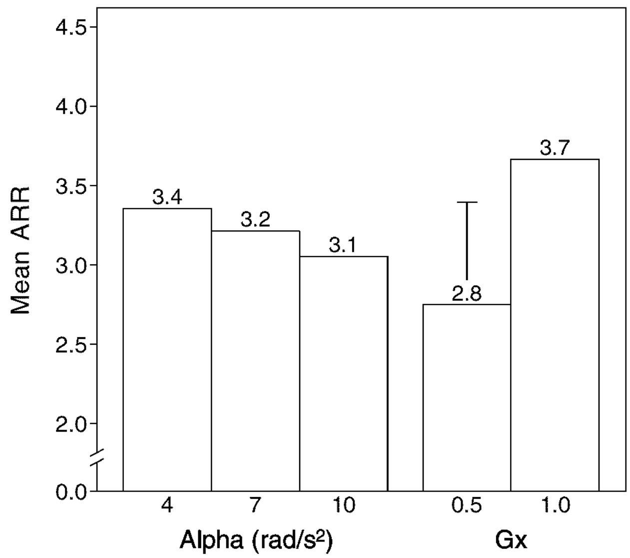

Figure 4. Main effect means. Gz=2.

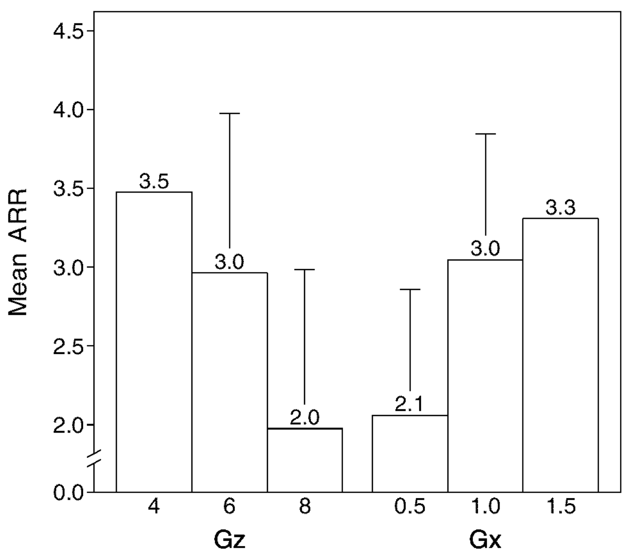

Figure 5. Main effect means. Alpha=4.

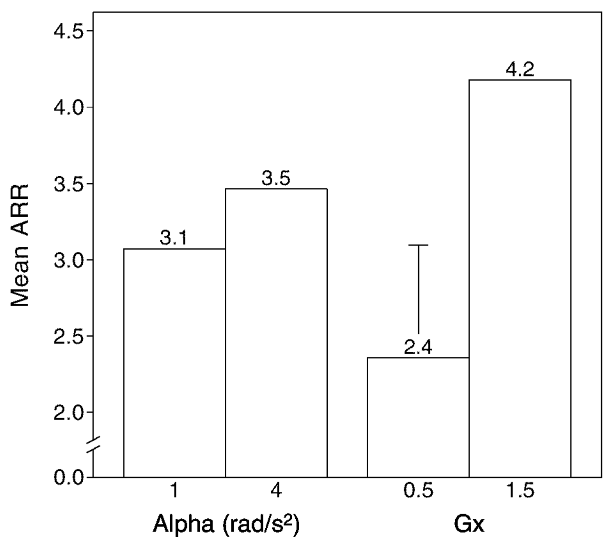

Figure 6. Main effect means. Gz=4.

Increase in the following Factor	Effect on Discomfort
Alpha	None
Gz	Decrease
Gx	Increase

Table 2. General findings of the Pitch analysis

Increase in the following Factor	Effect on Discomfort
Alpha	None
Gz	Decrease
Gy	Increase

Table 3. General findings of the Roll analysis

Test Summary- It was anticipated that very high alphas, such as 10 radians per second squared, would be deeply disturbing and possibly biodynamically dangerous. However, this was not at all the finding. The results indicate the effect of these artifacts to be no more than a mild disturbance over the expected range of G loading and artifact magnitudes. The tests also suggest that, for the range of accelerations tested, precision in Gx and Gy, as G magnitude increases, is more important than is precision in angular acceleration. Specific results of the tests are:

- Subjects preferred lower Gx and Gy to higher ones significantly.
- High angular accelerations (alphas) were slightly preferred to low alphas, but all alphas were comfortable, an unexpected result.
- Quicker transitions were preferred, especially at low Gz. At high Gz, the Gz seemed to mask this effect.

Conclusion

There appears to be no biodynamic reason to preclude the application of high fidelity, rapid acting, high torque gimbals to enable close matching of the rectilinear requirements. A centrifuge occupant will not be any more disrupted by the high angular acceleration artifacts associated with rapid response than they are by today's slower machines.

Credits

This work has been accomplished collaboratively under Cooperative Research and Development Agreements (CRDA) 96-AFIT-02 between Environmental Tectonics Corporation (ETC) and the Air Force Institute of Technology, and CRDA 99-141HE-01 between ETC and the Human Effectiveness Directorate of the Air Force Research Laboratory.

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